Single Photon Detection of 1.5THz Radiation with the Quantum Capacitance Detector

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Electron Beam Lithography by Richard E.Muller
Fresnel lens array by Daniel Wilson

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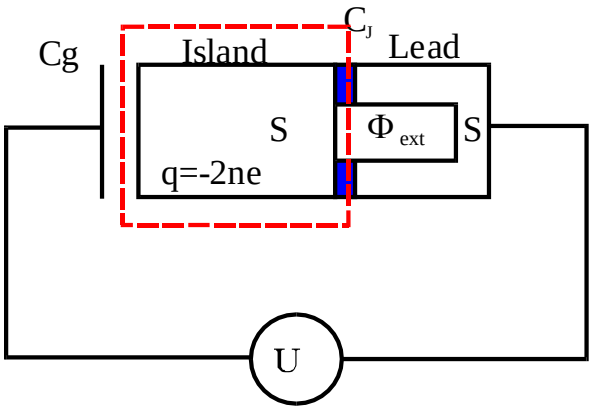
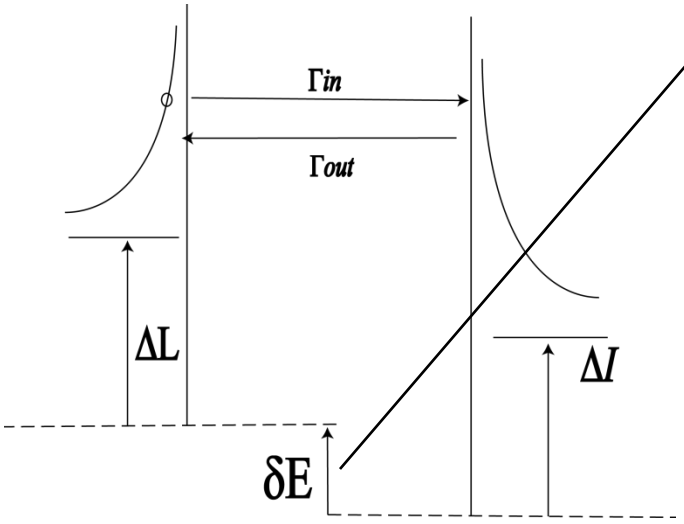
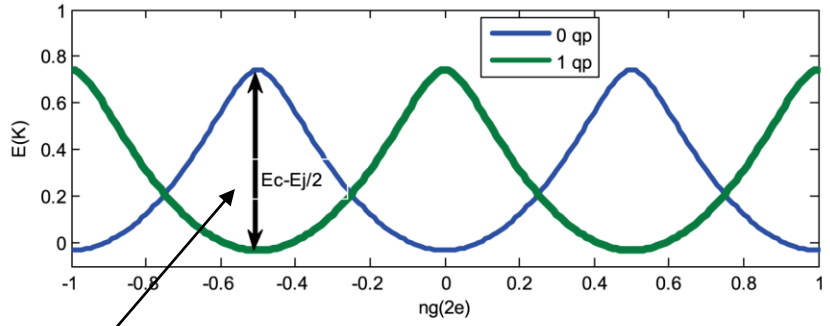
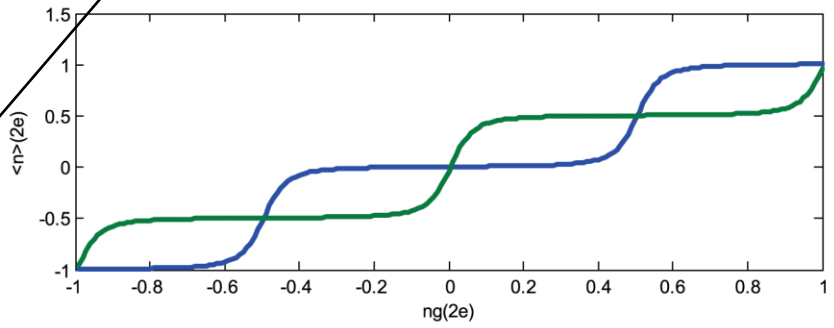
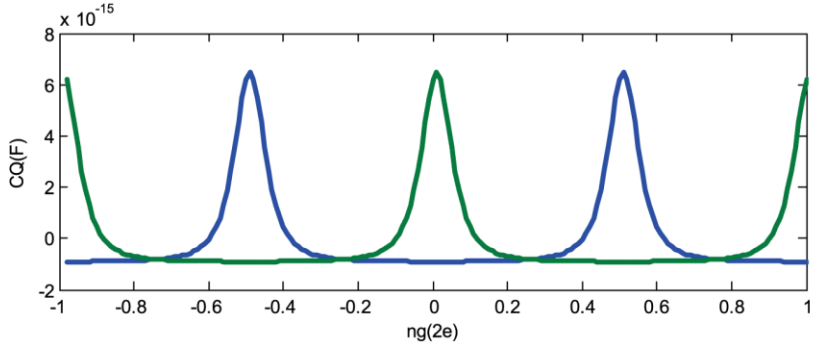
Single Cooper-pair Box (SCB)



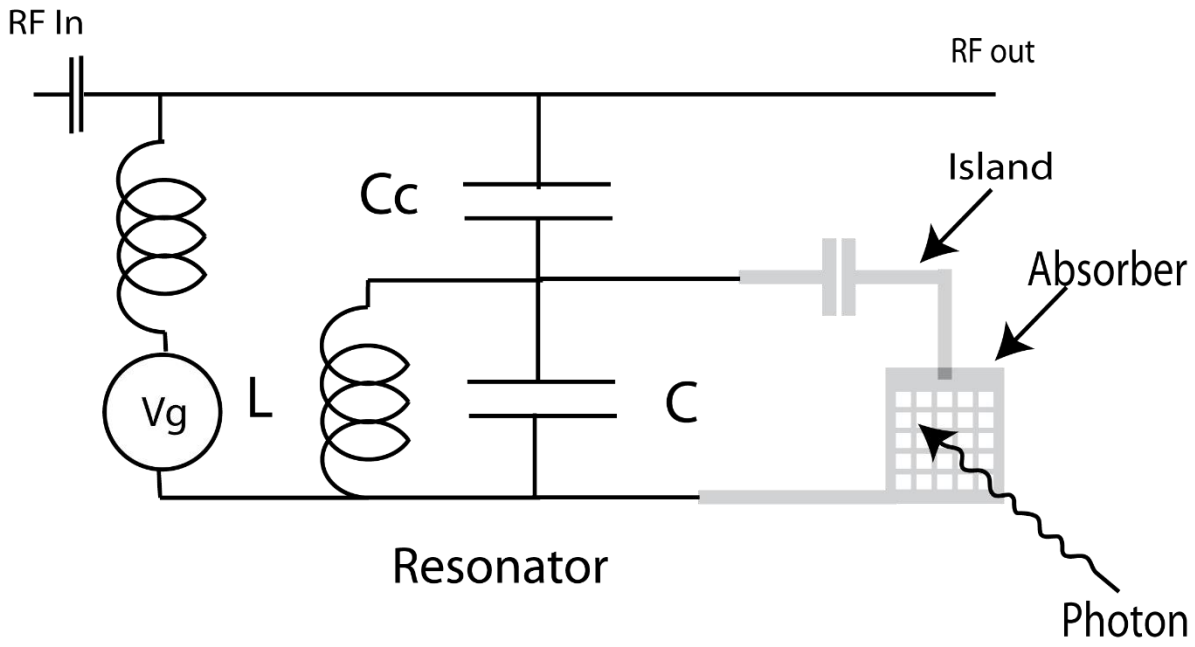


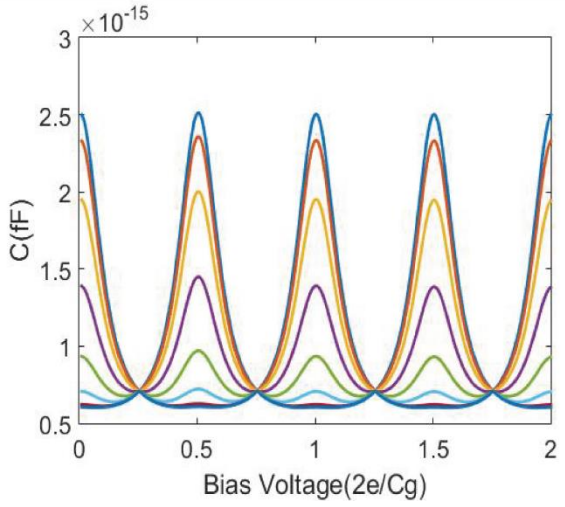


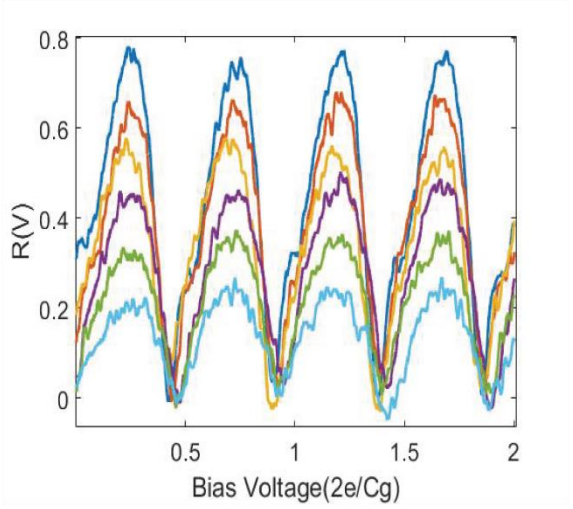




Quantum Capacitance Detector



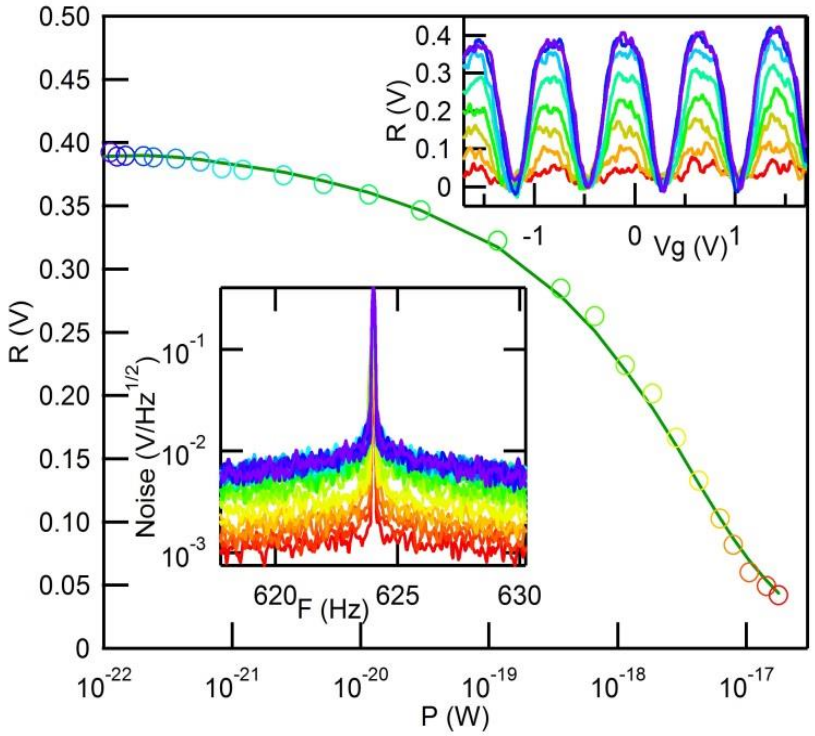




The Quantum Capacitance Detector

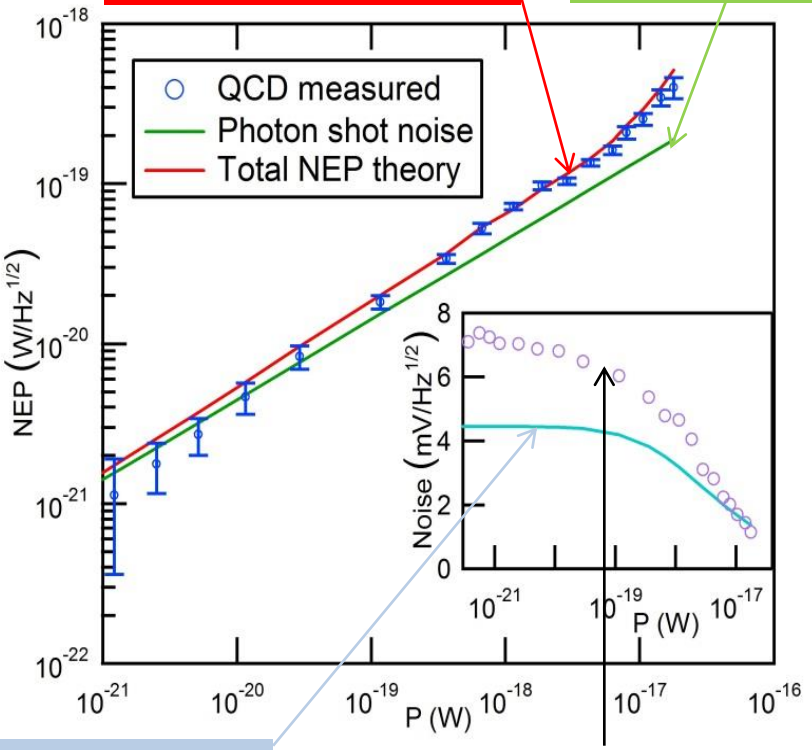
Response and noise as a function of optical signal

NEP as a function of optical signal
Photon shot noise limited!



$NEP_{tot} = \sqrt{NEP_{ph}^2 + NEP_{sn}^2}$

$NEP_{ph} = \sqrt{2hnP_s}$



Total measured noise

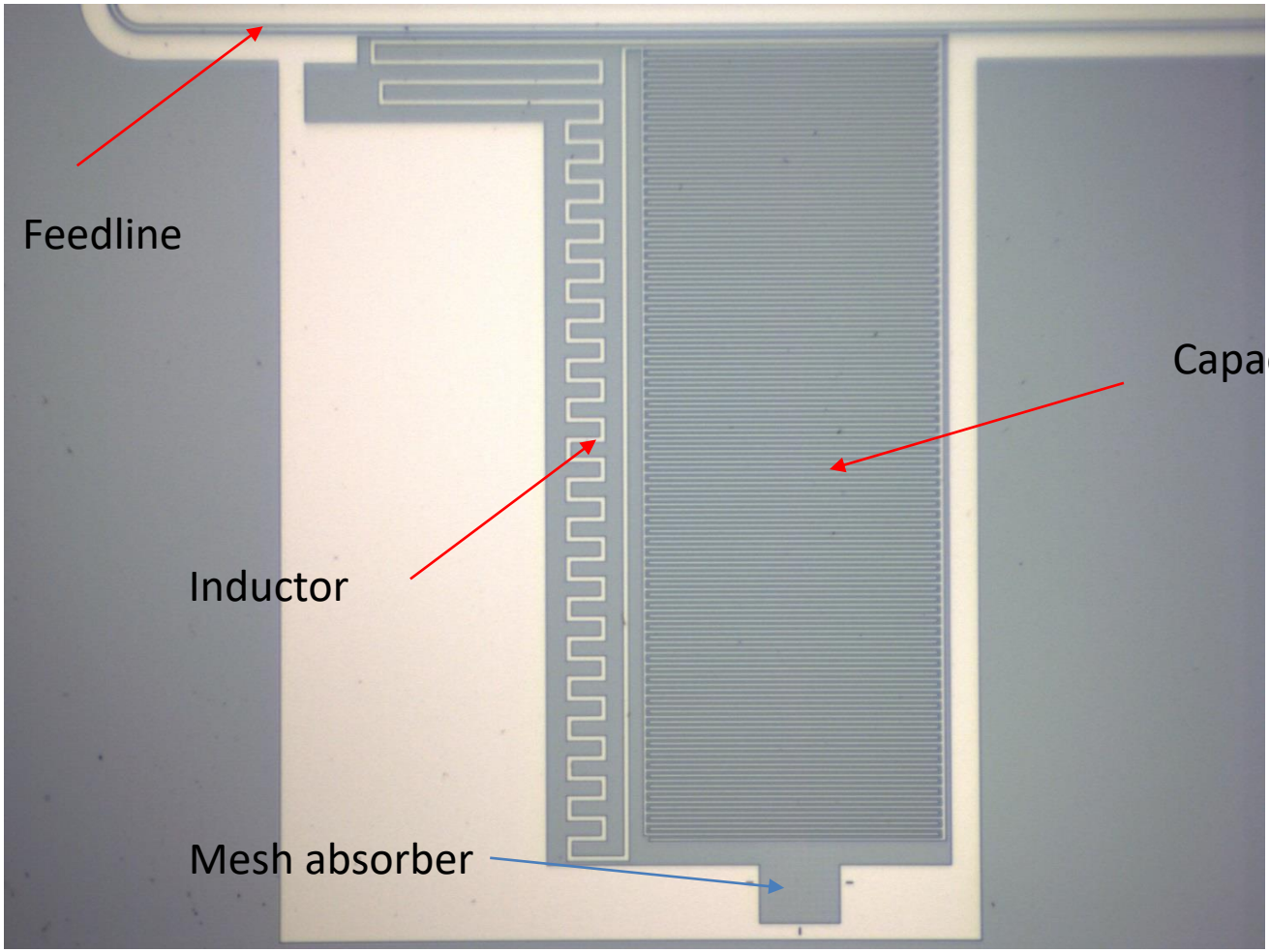
Shot noise of electron tunneling

$$S_{sn}(f) = \sqrt{2A^2(\Gamma_{in}\Gamma_{out}/\Gamma_{\Sigma})/(\Gamma_{\Sigma}^2 + (2\pi f)^2)}$$

$$NEP_{SN} = S_{SN}(f)/(\frac{dR}{dP})$$

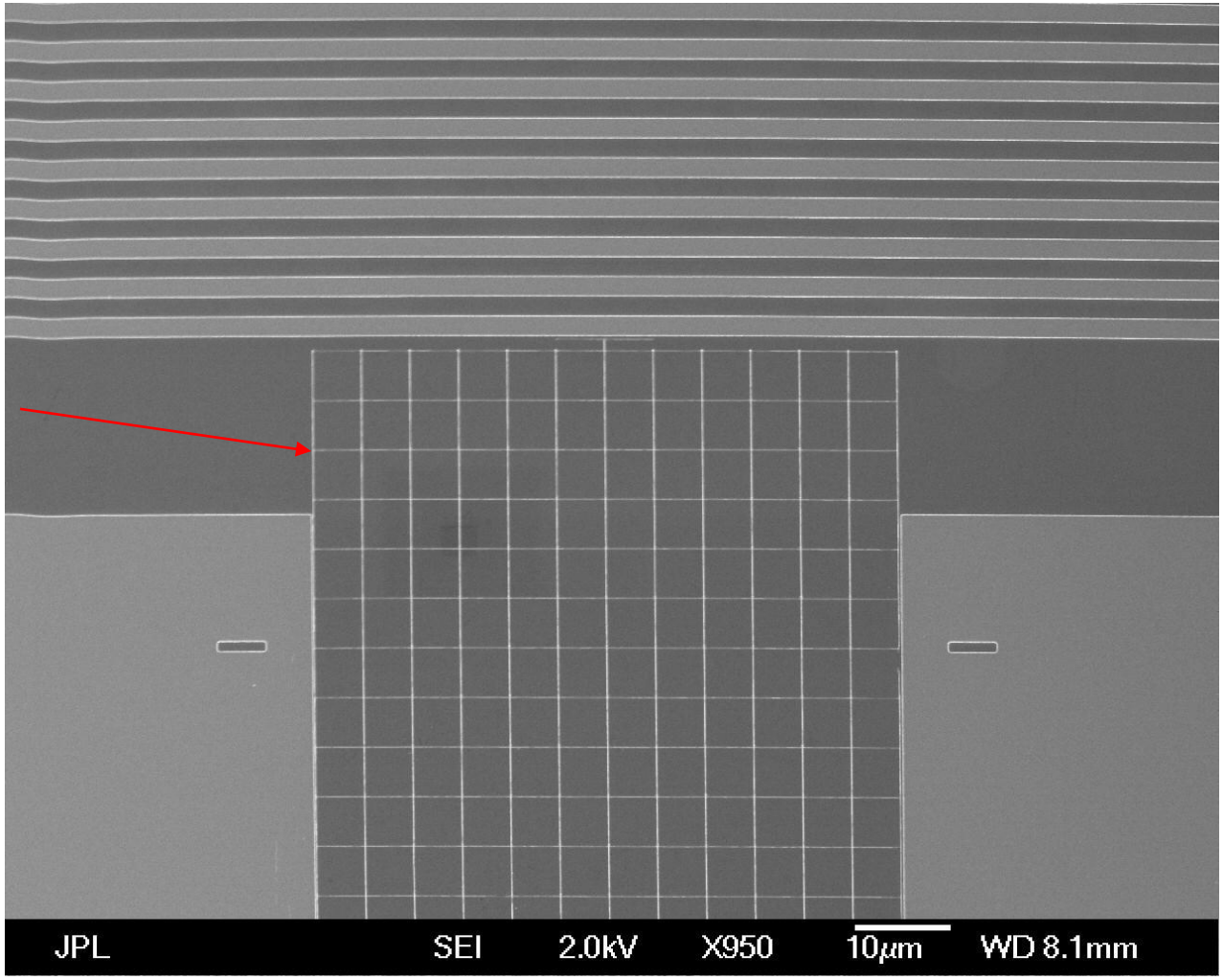
Lens coupled mesh absorber LEQCD

- Need mesh absorber instead of antenna to better couple to spectrometer modes
- Lumped element resonator saves space and has better characteristics than CPW half wave resonator

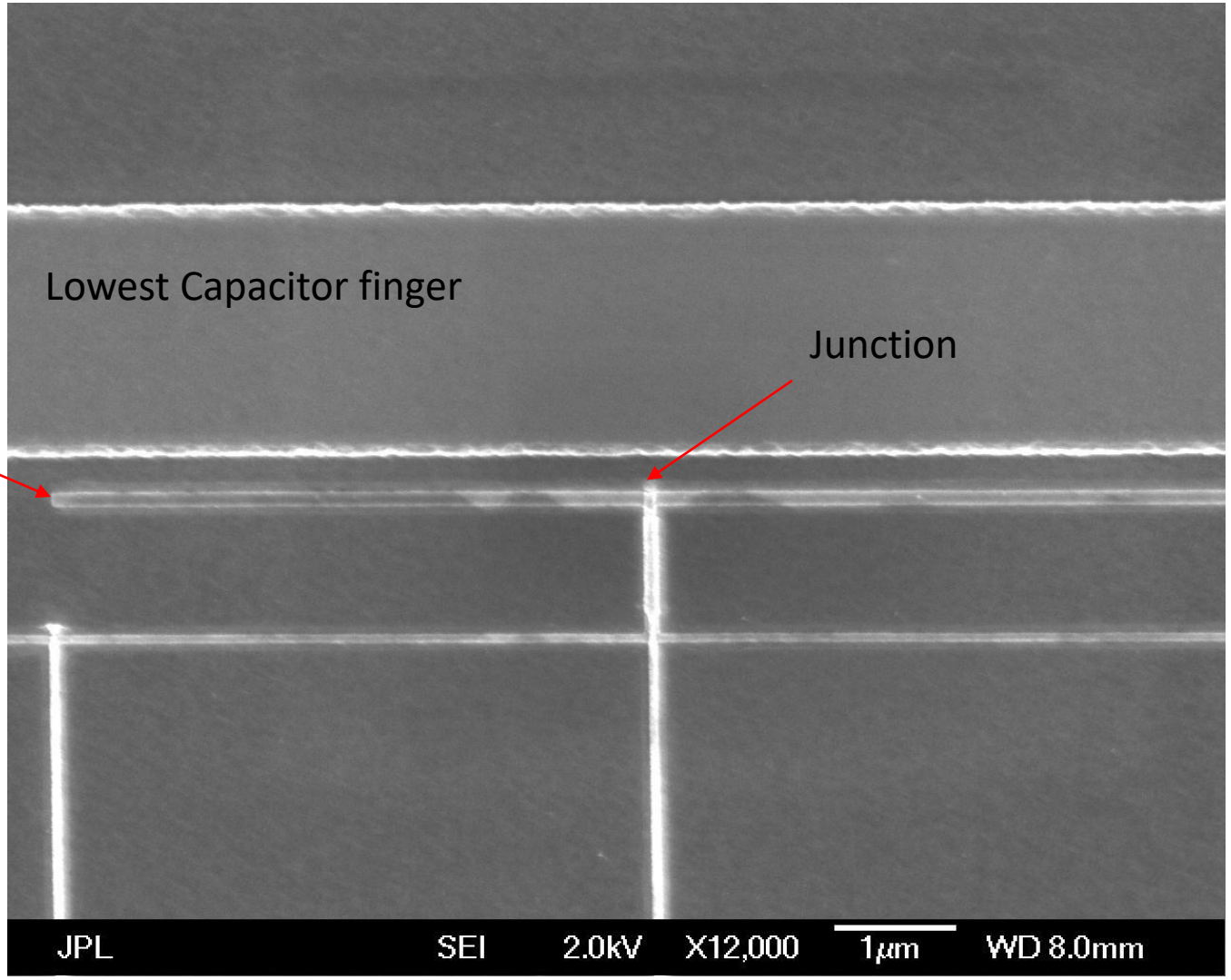


Lens coupled mesh absorber LEQCD

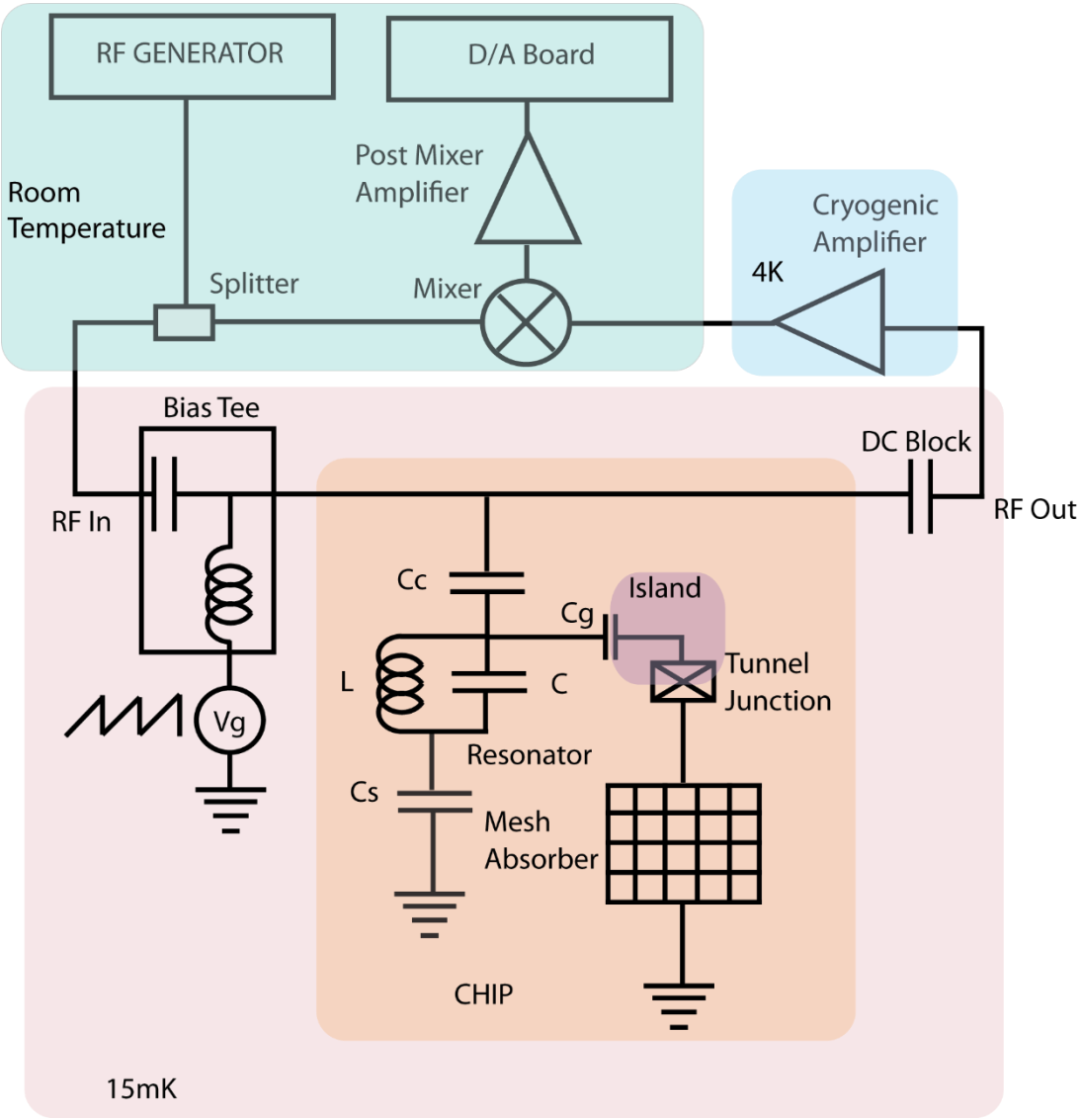
Mesh absorber



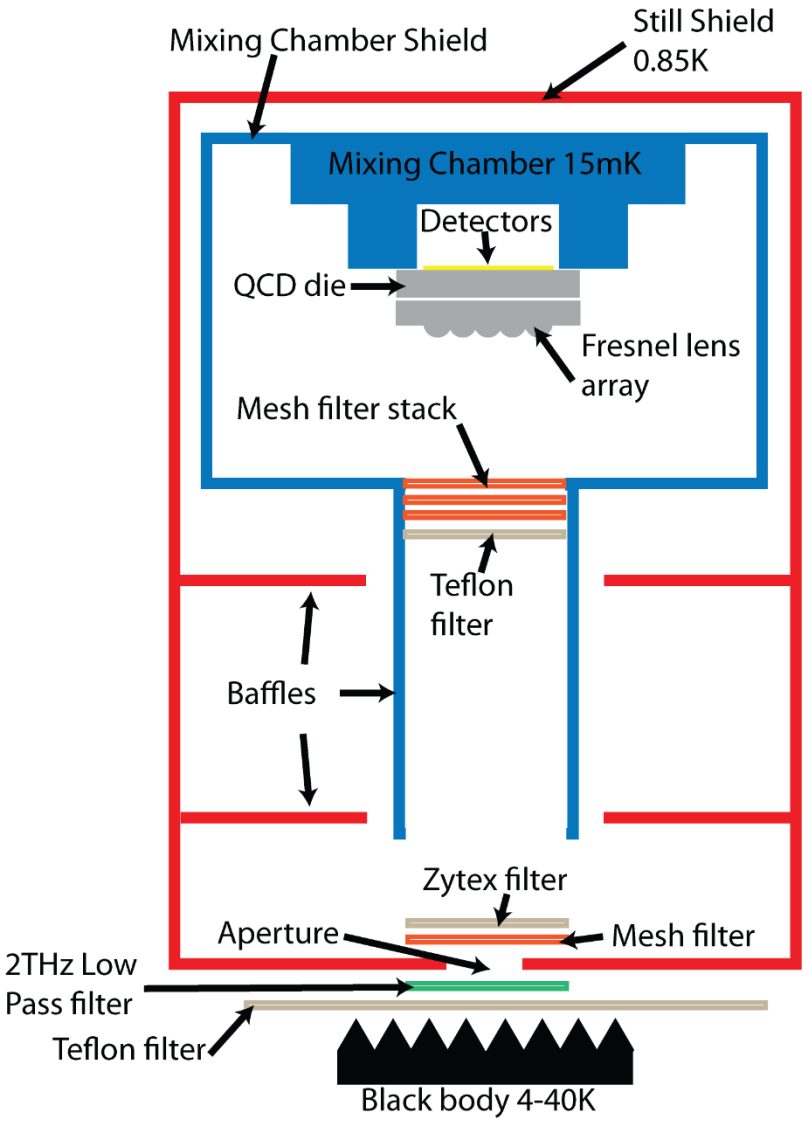
Lens coupled mesh absorber LEQCD



Measurement setup

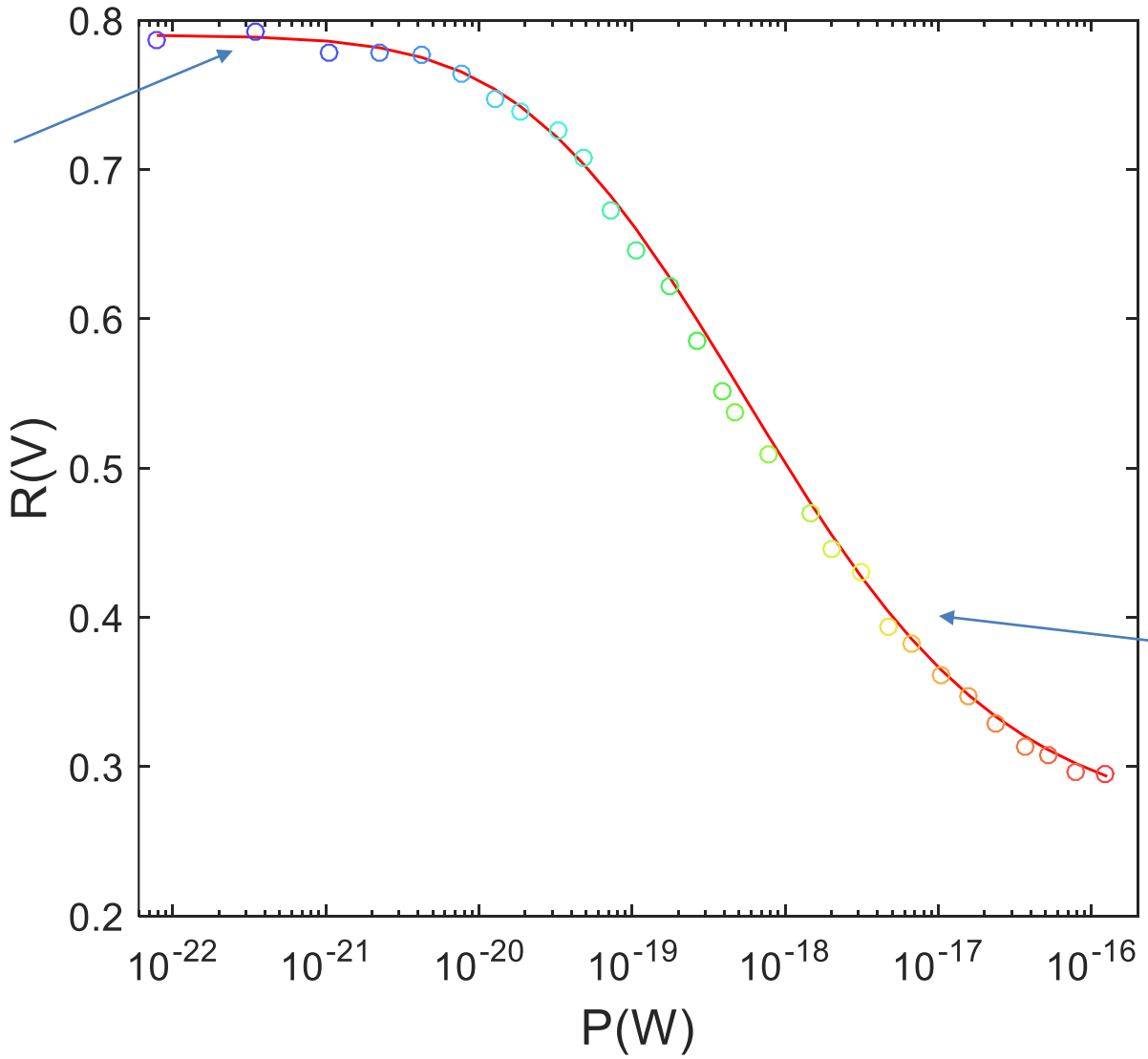


Measurement setup



Lens coupled mesh absorber LEQCD

- QCD response as a function of optical power

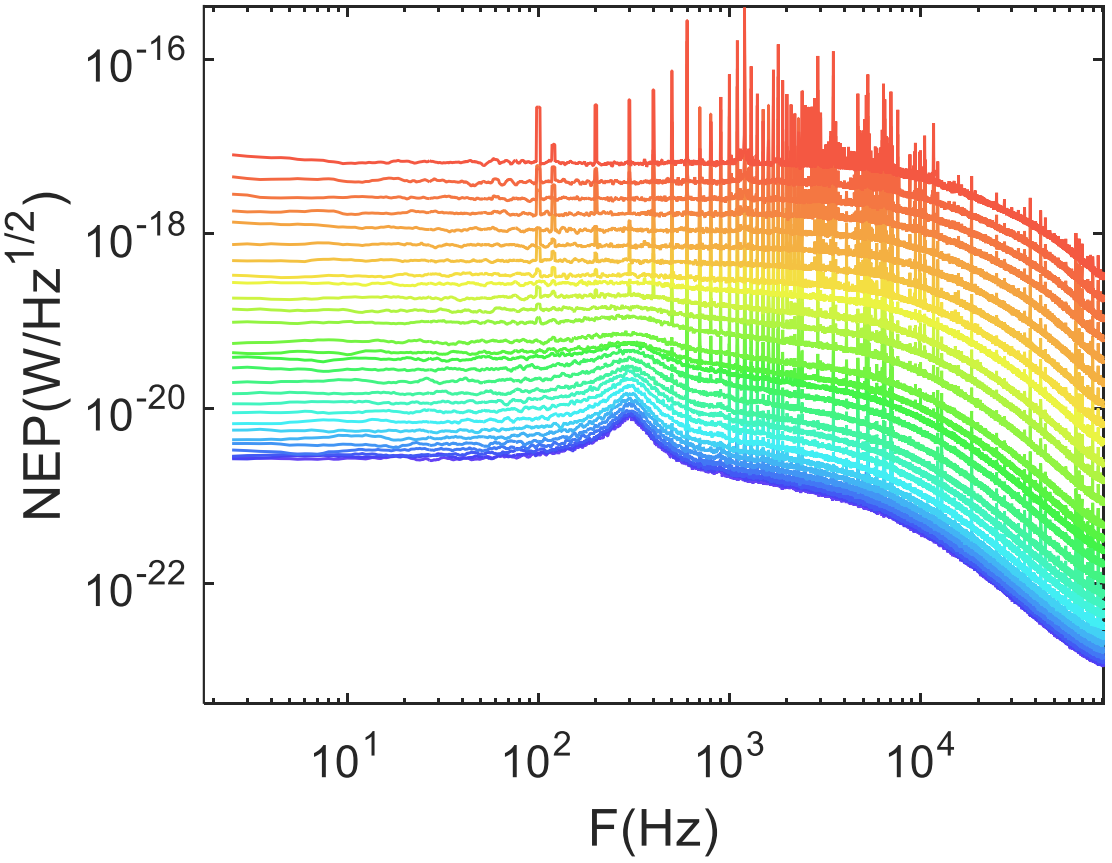


Tunneling in < base tunneling rate

Tunneling In >> Tunneling out -> Reaching saturation

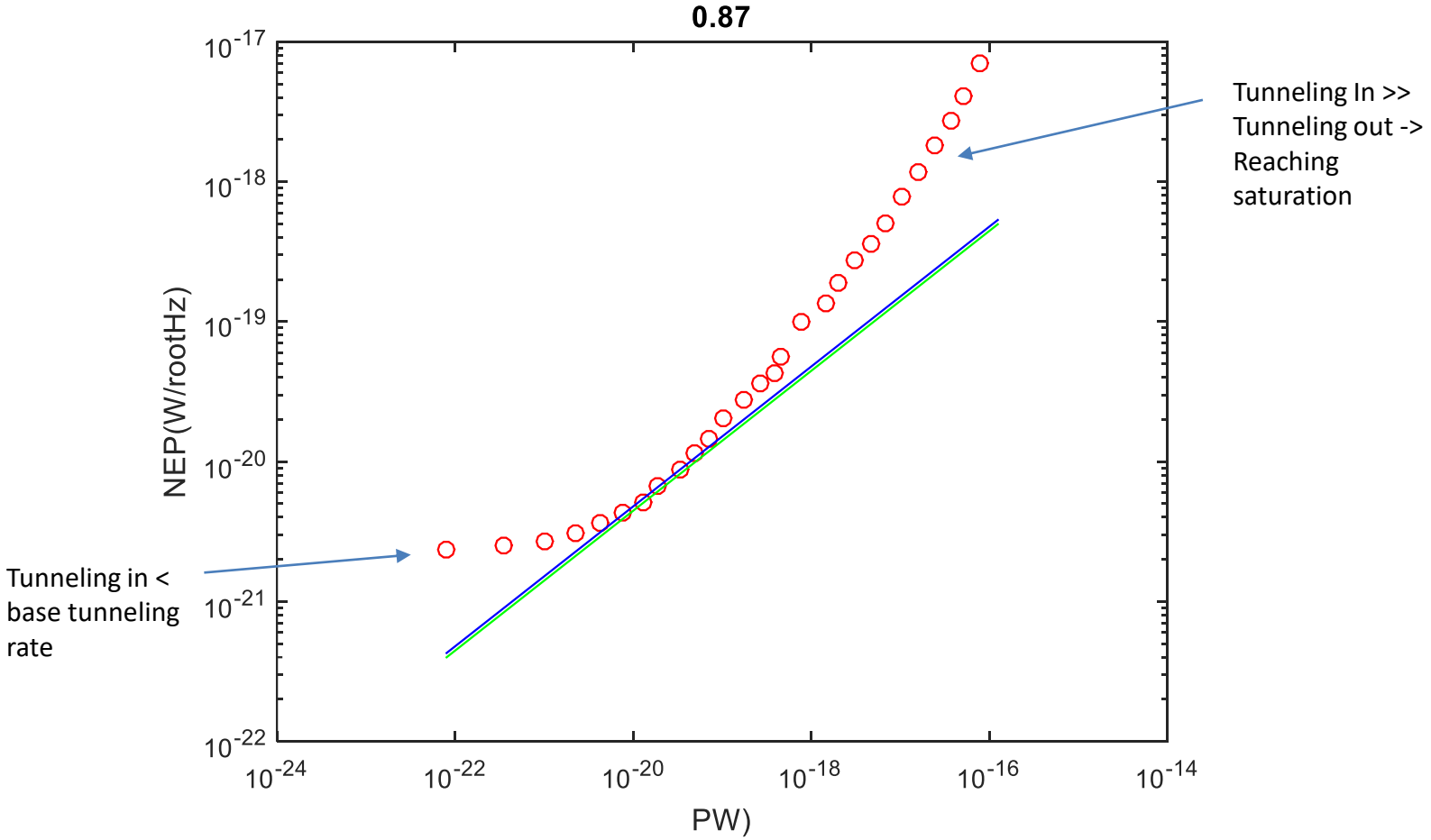
Lens coupled mesh absorber LEQCD

- NEP for various levels of optical illumination



- PSD time span 2s
- Gate sweep frequency 100Hz
- One sweep = 6 peaks
- QC peaks = 600Hz

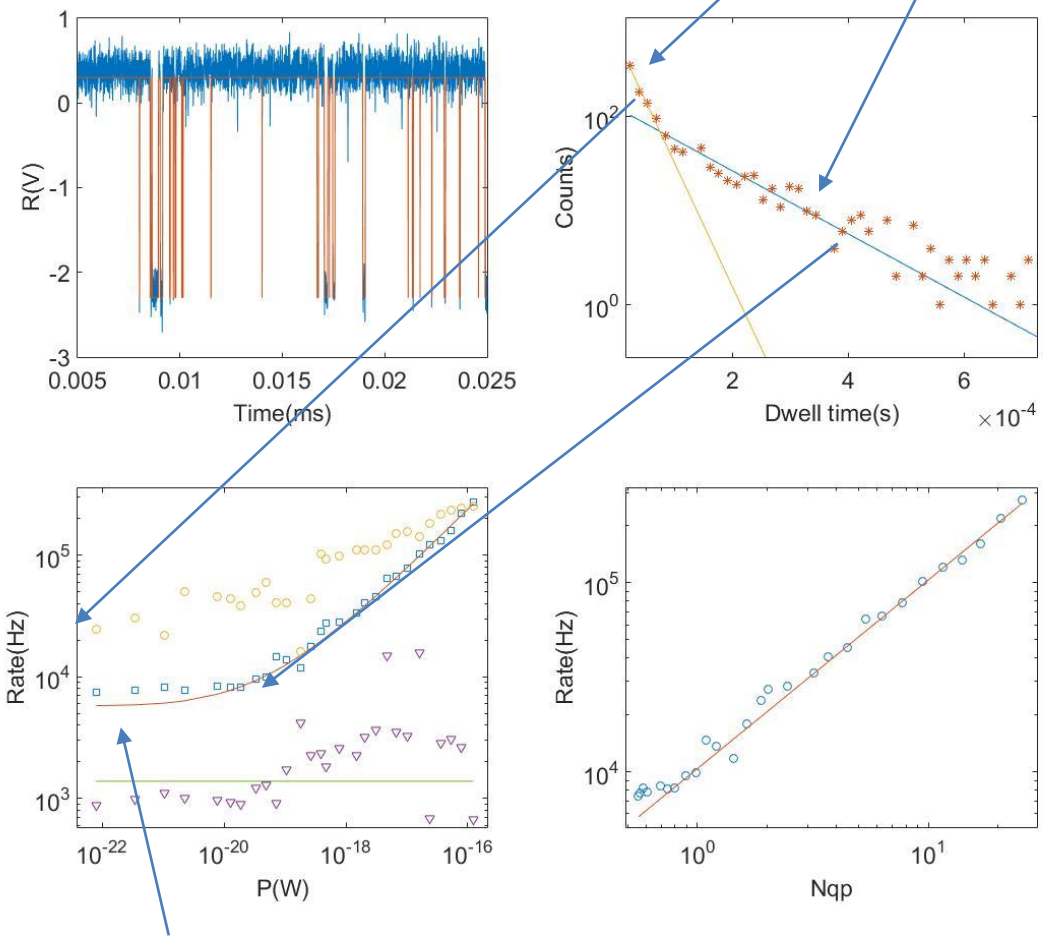
Lens coupled mesh absorber LEQCD



- $P^{1/2}$ dependence implies photon noise limited performance
- Efficiency extracted form ratio of measured NEP and photon shot noise NEP
- Should be able to detect single photons

Search for Single Photon Events – clues from DC biased time streams

$$\frac{dN_{qp}}{dt} = -RN_{qp}^2 - \frac{N_{qp}}{\tau}$$

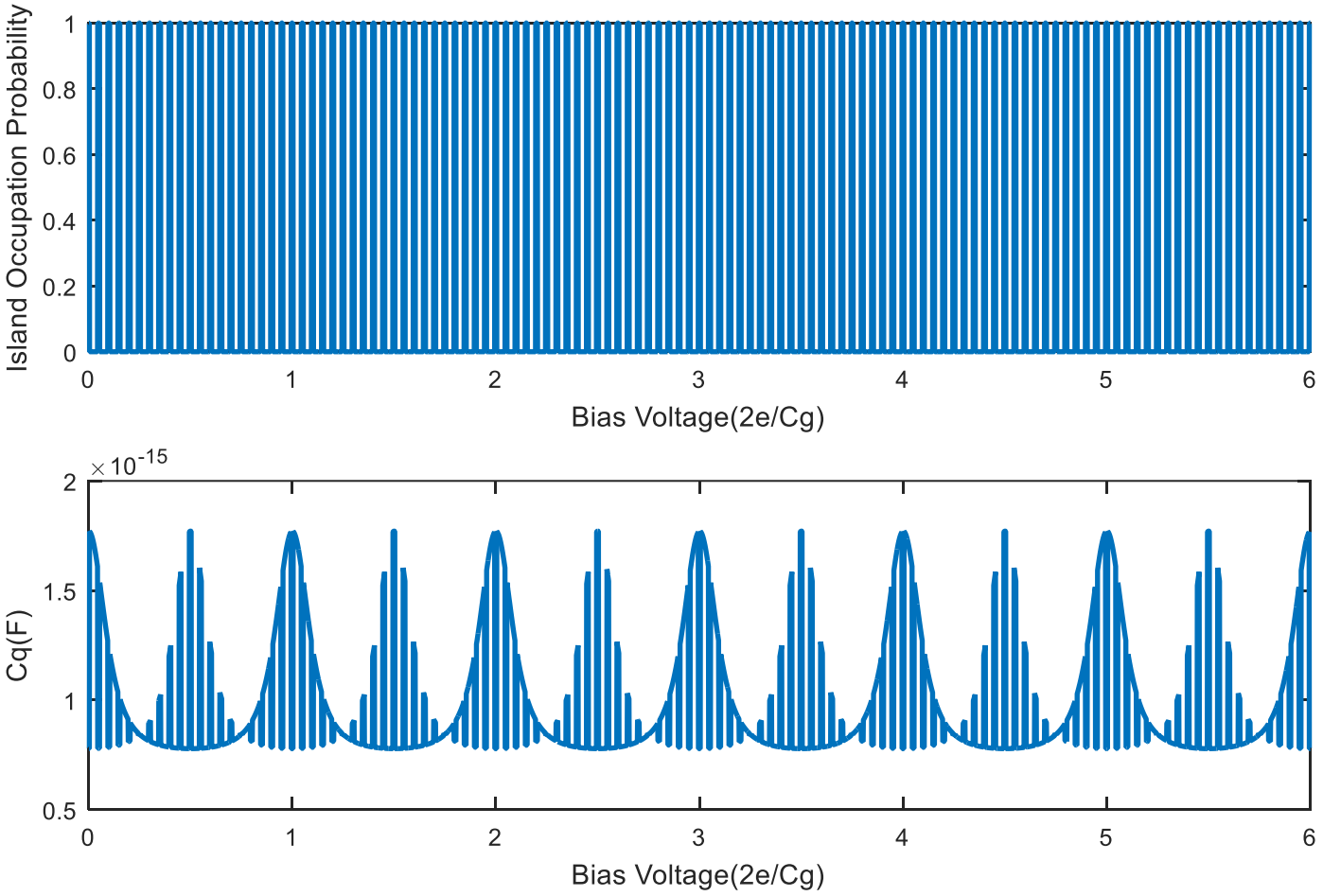


Background tunneling rate ~ 8kHz

- Measure time trace while DC biased
- Obtain histogram of dwell times
- Fit histogram to exponential decay
- Rate for longer times is due to residual lifetime
- Faster rate at shorter times due to single photons
- Tried to look for those faster events in smaller chunks of time stream – DAQ rate not fast enough to get good signal to noise ratio
- Can estimate how fast the initial tunneling rates are from the measured tunneling rates versus number of quasiparticles
- One photon generates on average 20 quasiparticles=> instantaneous rate about 220kHz

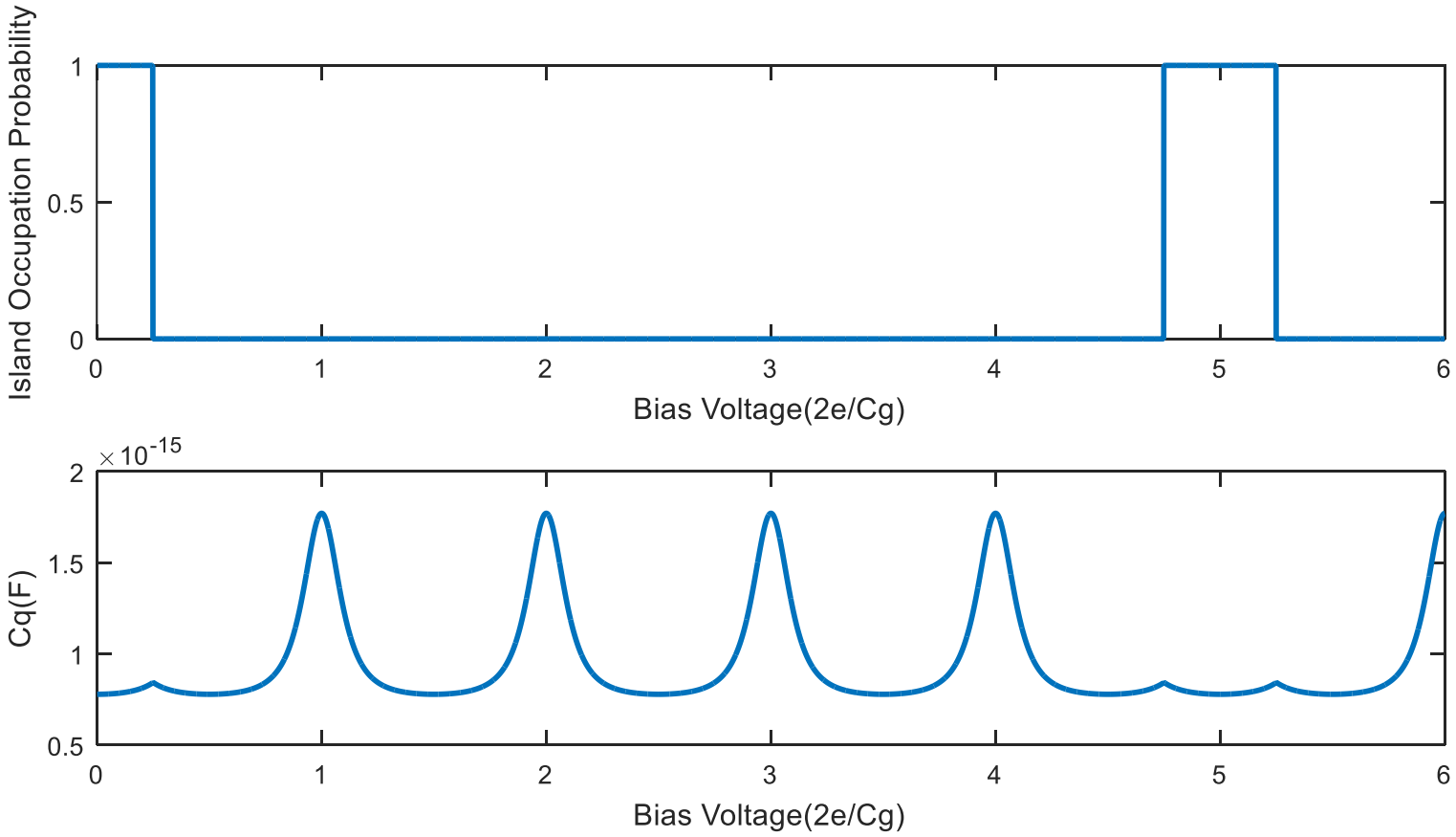
How to filter out background tunneling

Gate sweep frequency << Tunneling in rate



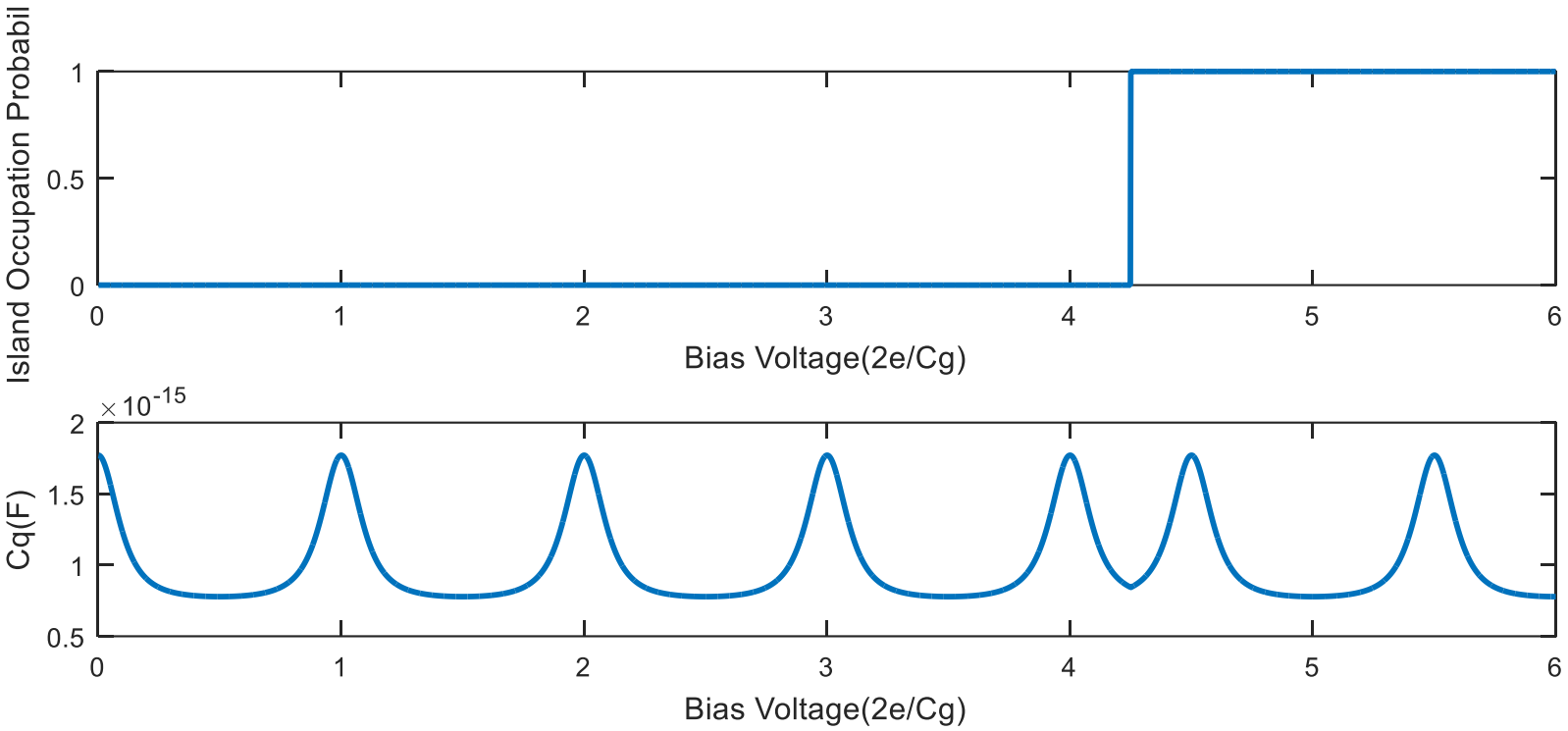
How to filter out background tunneling

Gate sweep frequency > Tunneling in rate – effect of photon absorption

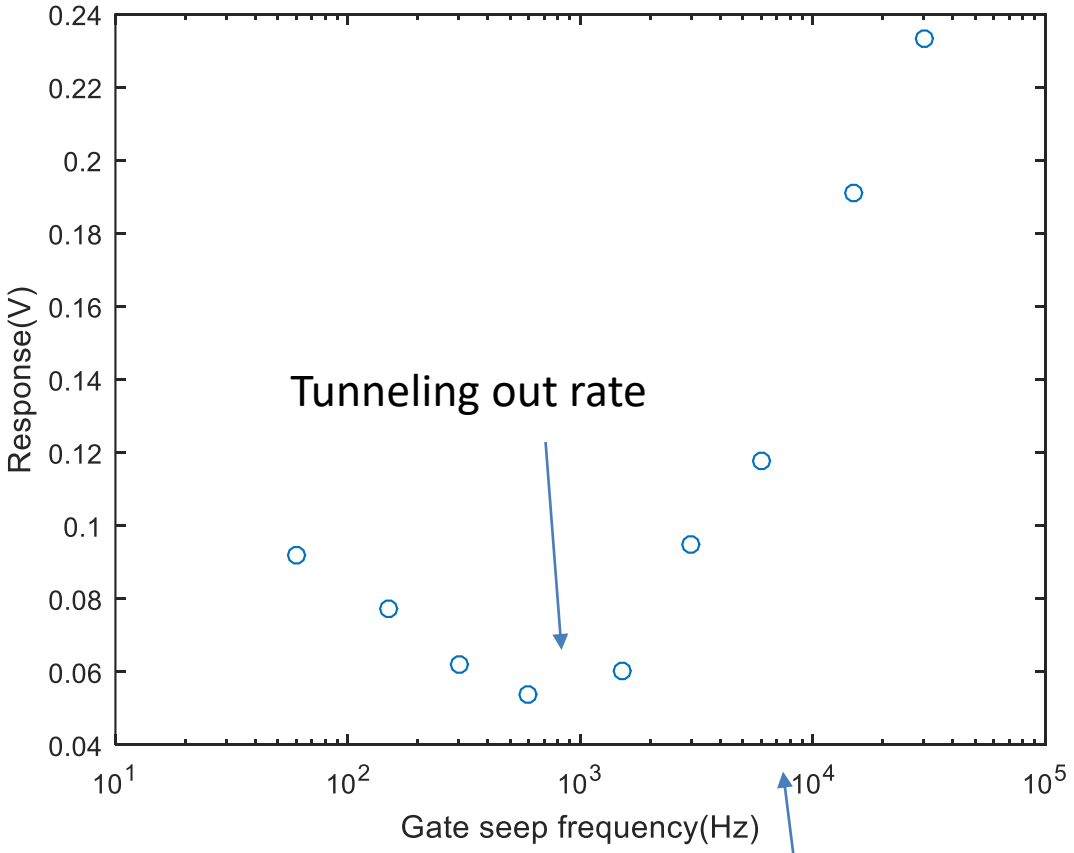


How to filter out background tunneling

Gate sweep frequency > Tunneling in rate – effect of background tunneling = e-shifts



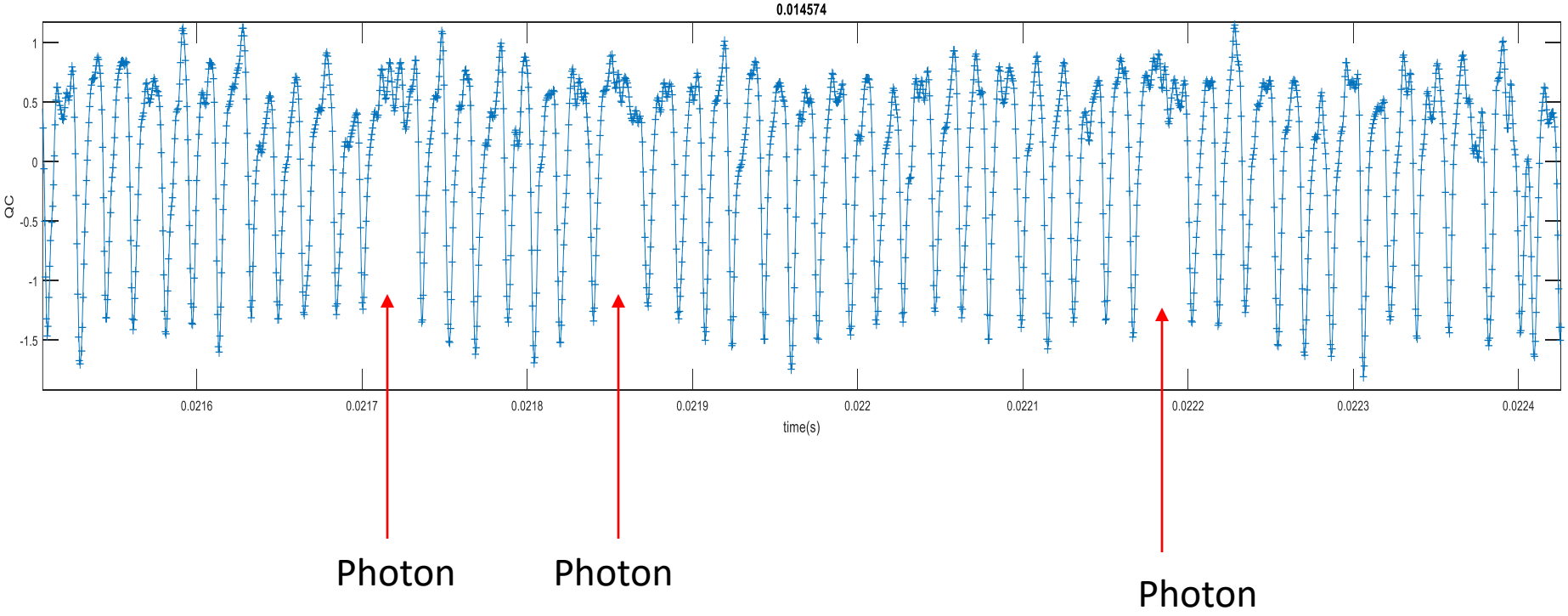
How to filter out background tunneling



Background tunneling in rate

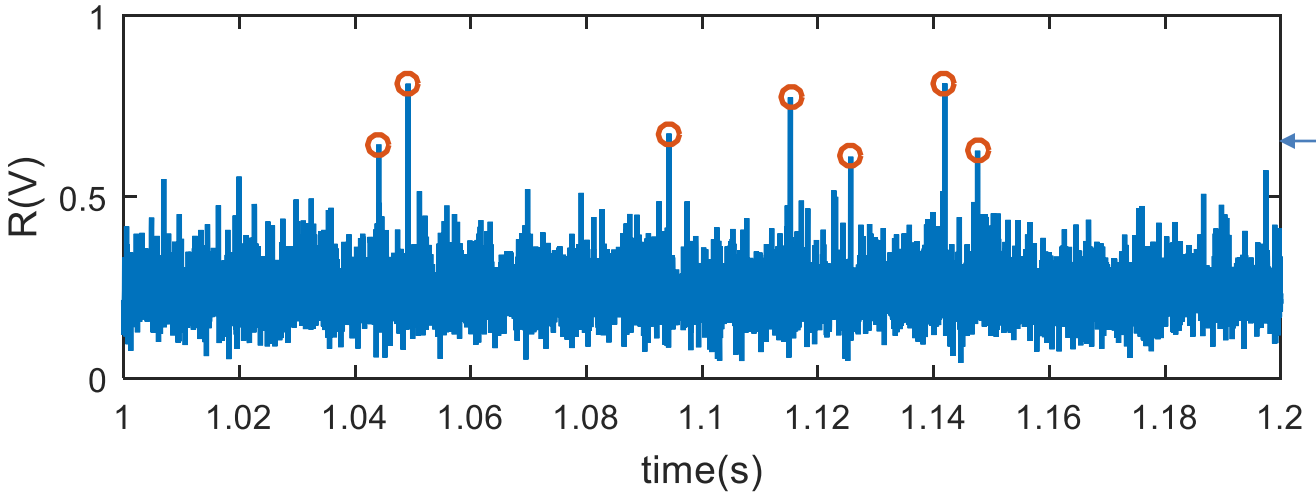
“ Fast sweep reveals single photon events spoiling QC signal

- Sweep rate ~ 22kHz spanning 3 Quantum Capacitance Peaks => effective sweep rate ~ 66kHz
- Should block background tunneling while still allowing tunneling due to single photon absorption
- Raw QC time trace should be absolutely periodic
- Gaps are due to high tunneling suppressing the Quantum Capacitance signal
- Therefore Gaps should be due to single photon absorption

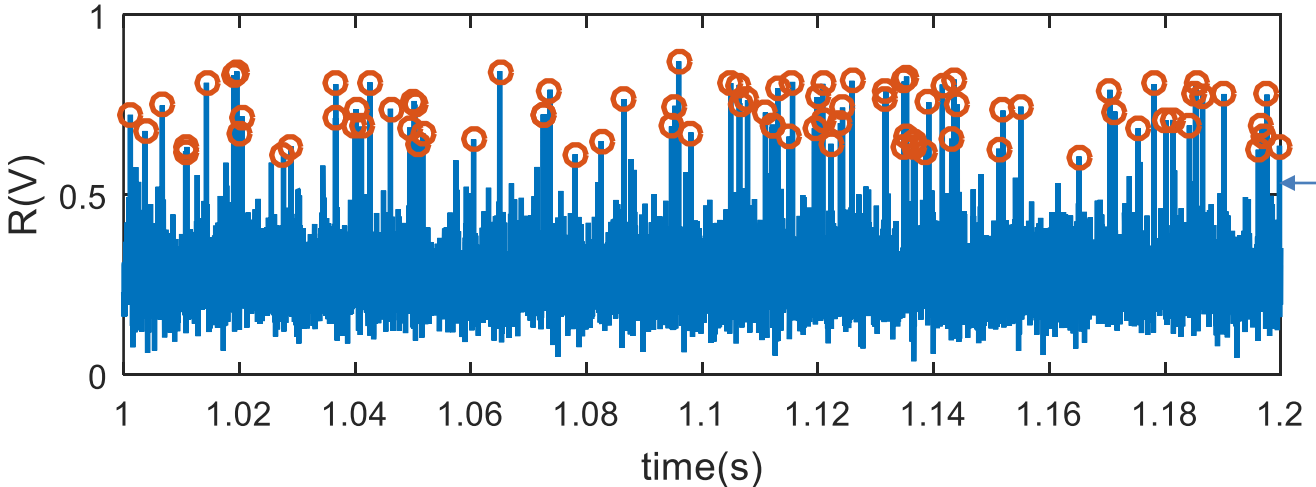


Variance evaluated in 30 us bins shows photon events

- From time traces calculated variance of slices corresponding to 2 QC peaks (to avoid problems at the edge of sweep with e-shifts) – slices are 30µs long
- Subtracted this trace from the maximum of the traces
- Gaps in the Quantum Capacitance trace will show up as peaks
- Repeat for different black body source temperatures



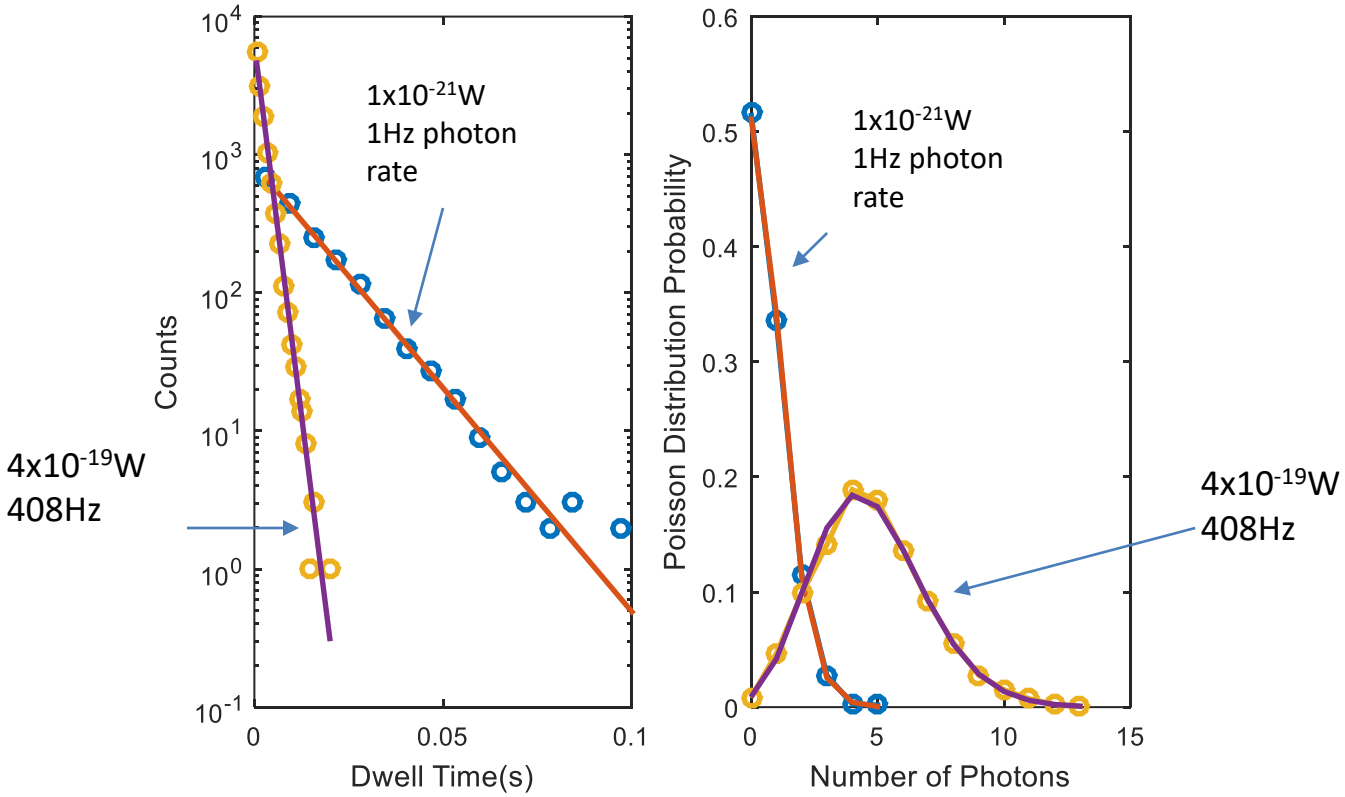
$1x10^{-21}$W
1Hz photon rate



$4x10^{-19}$W
408Hz

Photon arrival intervals follow Poisson statistics

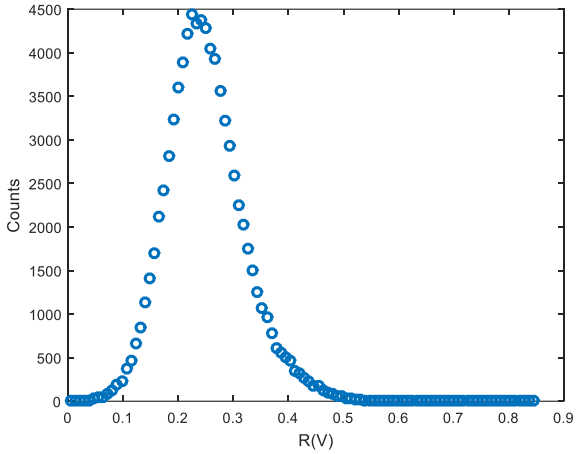
- From the photon time traces, extract dwell time histograms – exponential decay corresponds to Poisson statistics
- Calculate probability of having N photons within a time interval 36ms (Arbitrarily picked)
- Plot probability x number of photons; blue circles is measured, lines are calculated Poisson distribution probability (no fit, just using measured average number of photons)



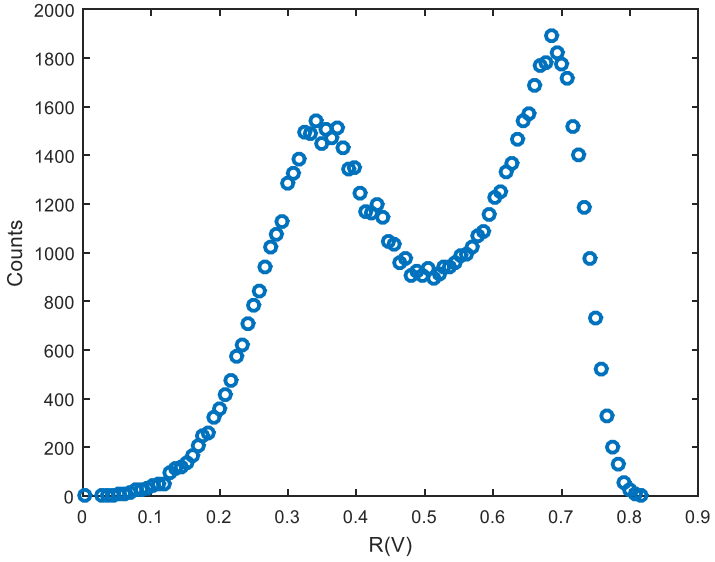
Photon arrival statistics

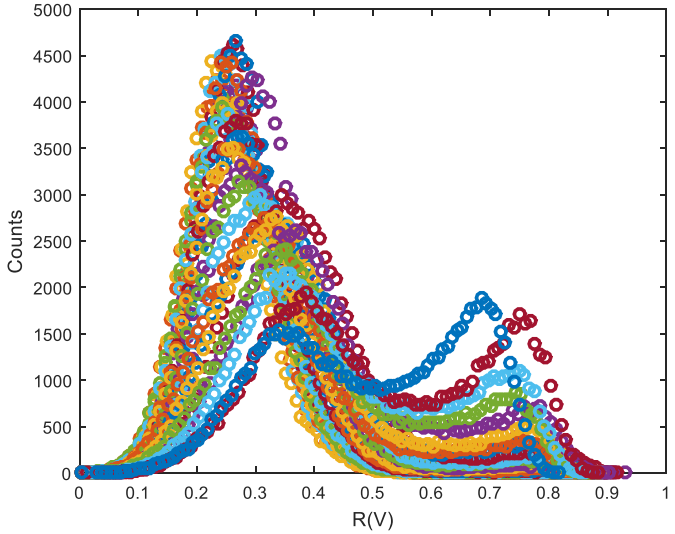
Histogram of response for various black body temperatures
For cold black body only peak around 0.25 exists
For hot black body peak around 0.6-0.7 is larger than peak at 0.25

Cold black body



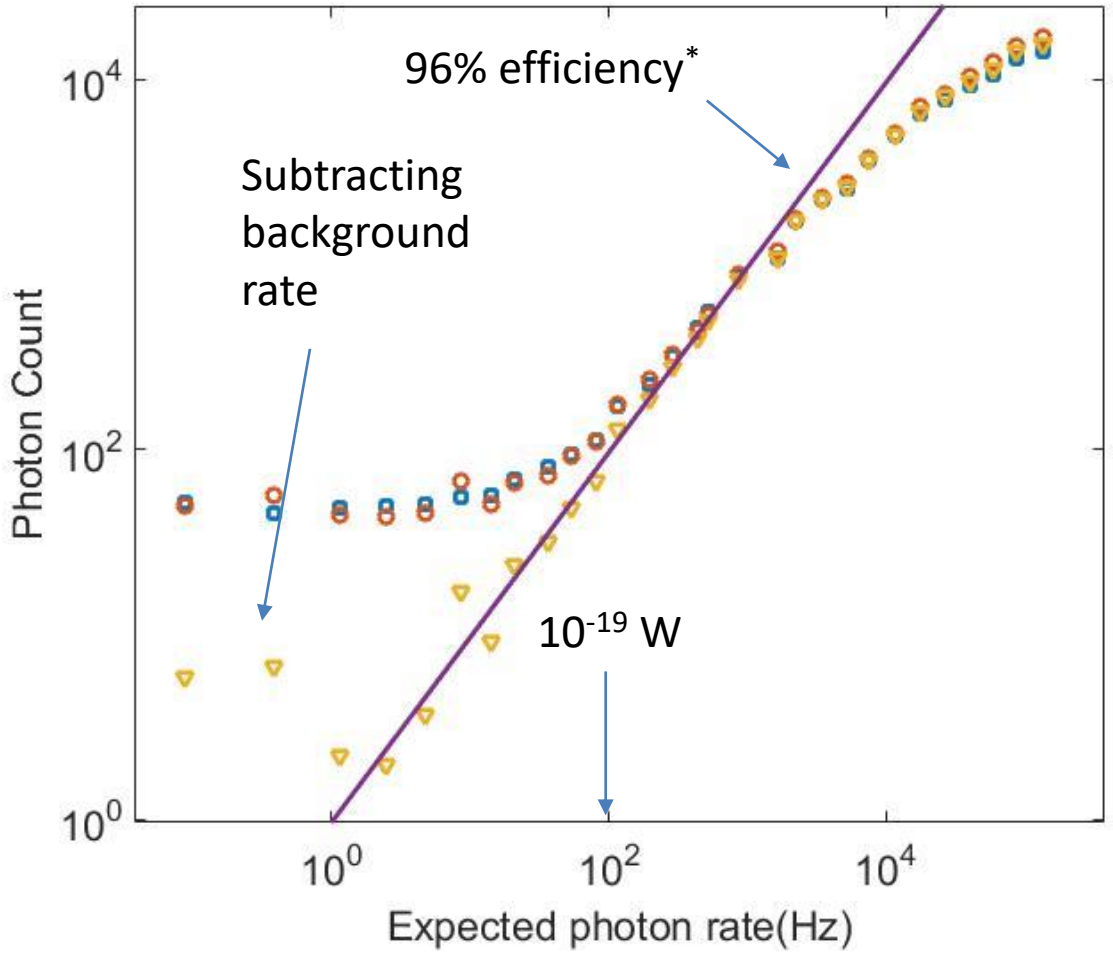
Hot black body





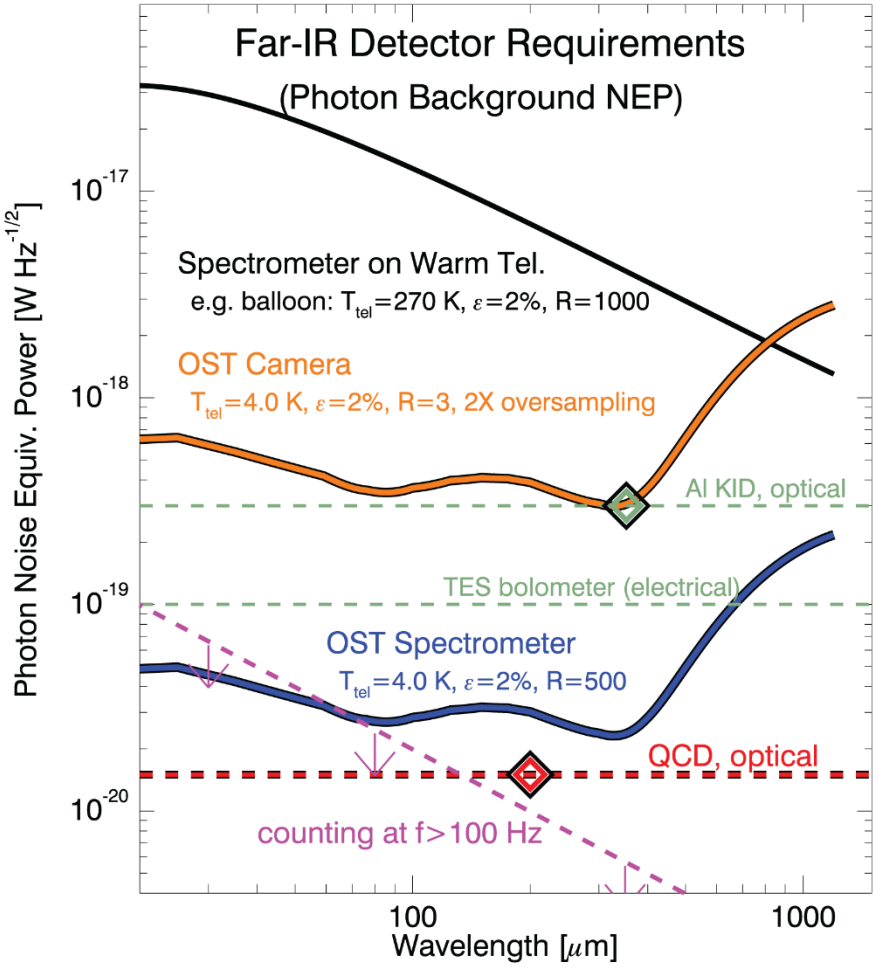
- Peaks get closer together at high black body temperatures due to filtering by the resonator of the high frequency stream
- Could lower resonator Q by stronger coupling at the expense of fewer channels

Counts of response between 0.6 and 0.9 versus number of expected photons



- Efficiency will decrease with when time intervals between photons become comparable to the time separation of two Quantum Capacitance Peaks

* With respect to absorbed power

Conclusion

- QCDs shot are noise limited at 10^{-19}W of optical loading
- Single Photon Counting at 1.5THz from 10^{-19} to 10^{-17}W demonstrated
- Large format arrays possible with frequency multiplexing
- Good candidate for a detector array in a cold far-IR spaceborne telescope